Focus Topic: Waves in ice

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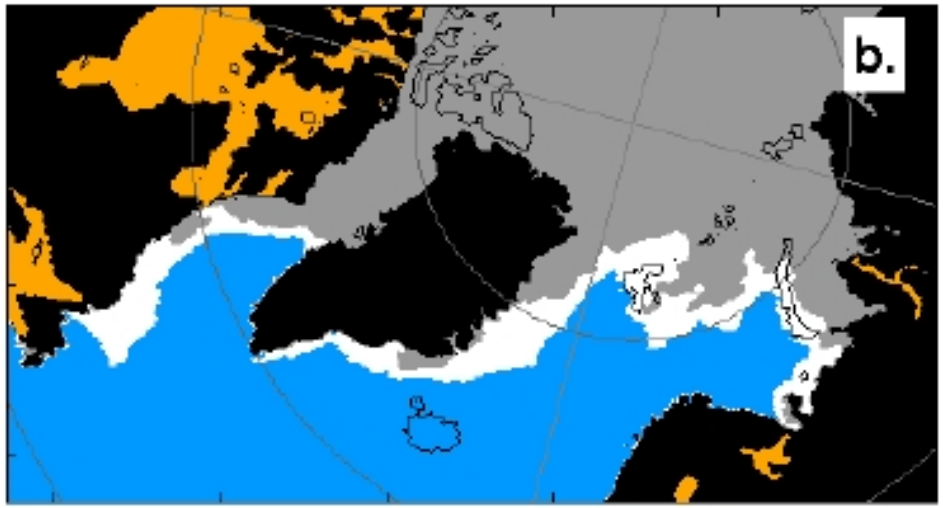
Marginal ice zone (MIZ)

Peter Wadhams (1986) defines the marginal ice zone as:

'that part of the ice cover which is close enough to the open ocean boundary to be affected by its presence'

However:

- There is no precise MIZ definition.
- Some use concentration, e.g. Strong (2012) defines the MIZ as $0.15 \leq c < 0.8$ (see right).
- My group uses the area of wave-broken ice.

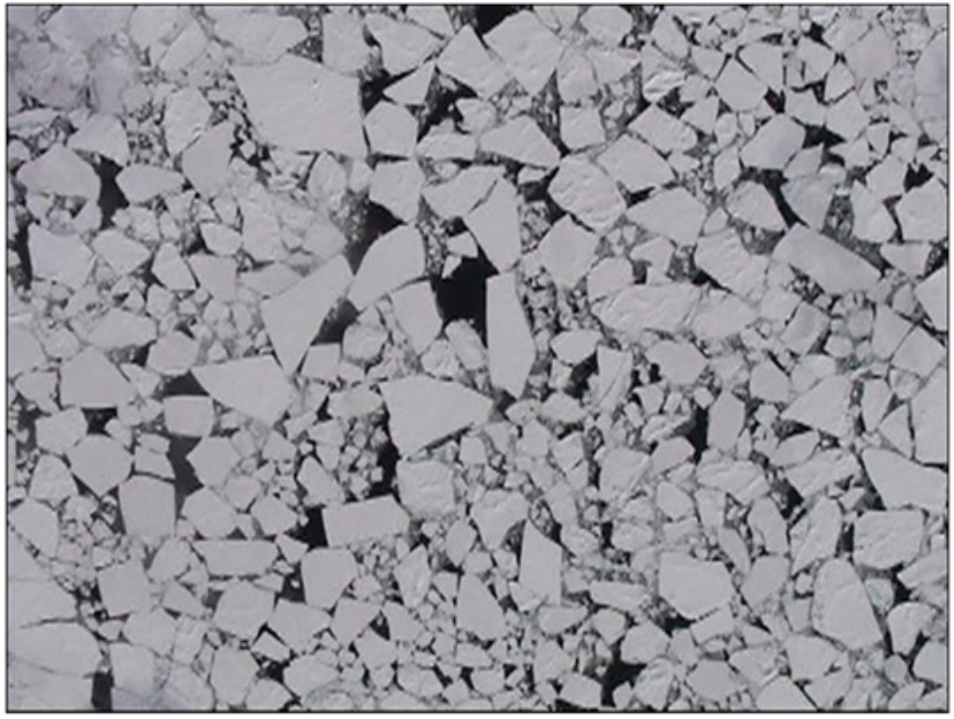


Pack ice (grey), MIZ (white), sparse ice (blue), land (black) and enclosed water (orange). From: *Strong (2012) J. Clim. Dyn.*

Marginal ice zone (MIZ)

MIZ basics

- Floes relatively small $\sim \mathrm{O}(10 - 100)$ m diameter.
- Floe sizes increase from edge.
- Surface waves are present.
- Floe size distribution is created by the waves.
- Antarctic MIZ is large proportion of pack ice ~ 100 km in width.
- Arctic MIZ: Bering, Greenland, Labrador, Barents Seas.



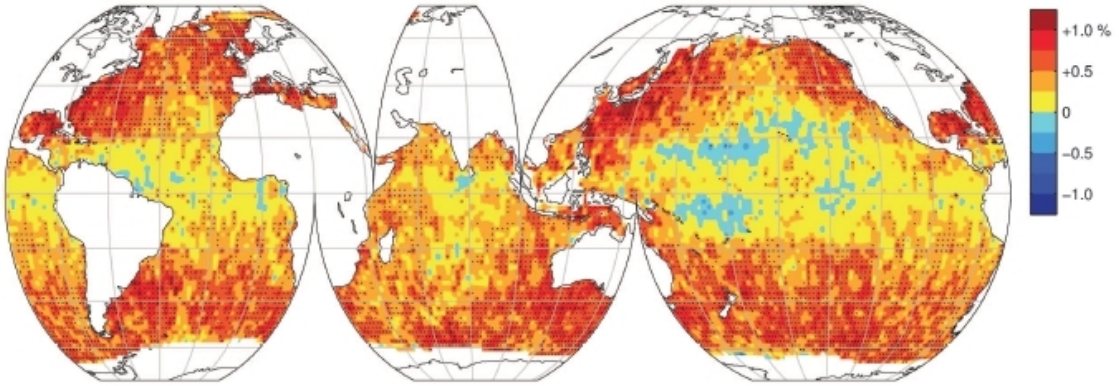
From: *Toyota et al (2011) Deep Sea Res.*

Marginal ice zone (MIZ)

MIZ and climate change

- Climate warming has weakened (Arctic) sea ice.
- Waves are becoming more more intense in higher latitudes (see below).
- MIZ-type conditions are/are likely to become more prevalent.
- Prinsenberg & Peterson (2011) report swell-induced failure of multi-year ice far from ice edge in Beaufort Sea, 2009.

99% Sig. Wave. Height (1985-2008)



From: *Young et al (2011) Science*

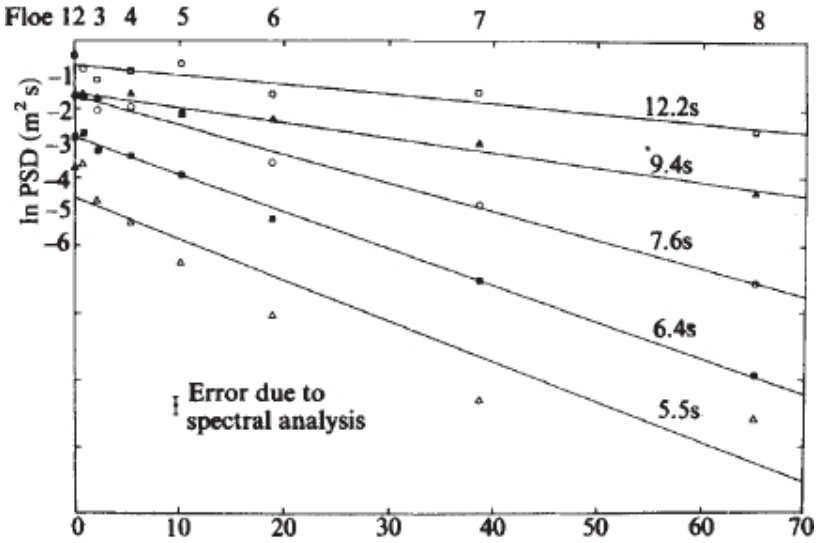
Wave attenuation

Attenuation basics

- Waves attenuate (approximately) exponentially with distance into the ice-covered ocean.
- The ice acts as a ‘low-pass filter’.
- Scattering by ice edges and ‘features’ (cracks, ridges, etc) is believed to be the dominant cause of attenuation.
- Other possible causes of attenuation are: inelasticity/hysteresis, floe-floe collisions, turbulence, drag.
- These processes dominate for large wave periods.
- ‘Rollover’ is also evident for small periods and may be caused by fetch or non-linear transfer of wave energy.

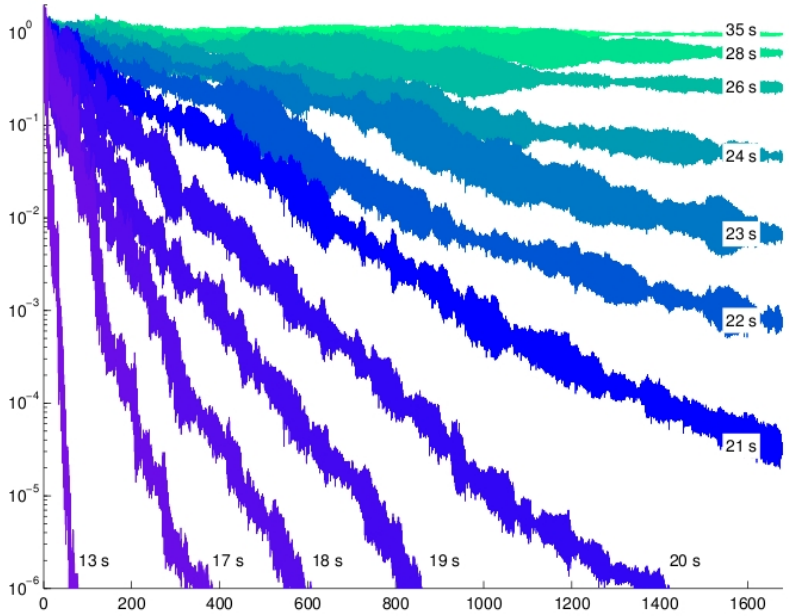
Wave attenuation data

Experiment



From: *Squire & Moore (1980) Nature*

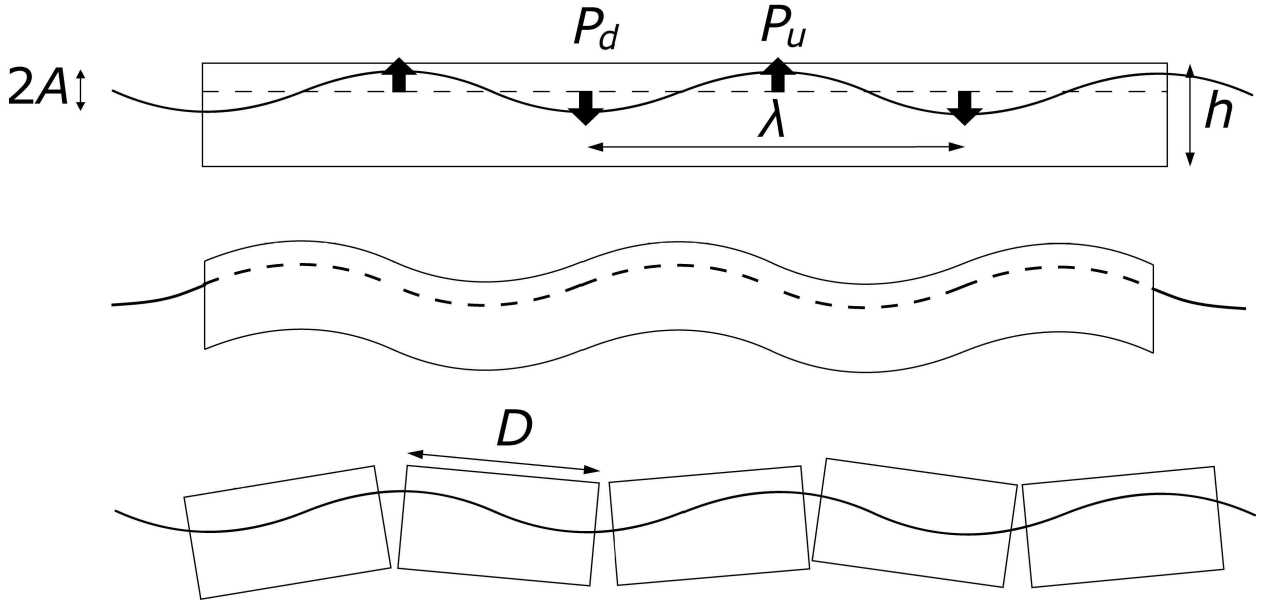
Model



From: *Squire et al (2009) Geophys. Res. Lett.*

Floe breaking

- Ice bends & flexes in response to the waves.
- Bending imposes a strain on the ice.
- If the strain is large enough the ice will fracture.
- Other factors could also cause fracture, e.g. stress due to cavitation.

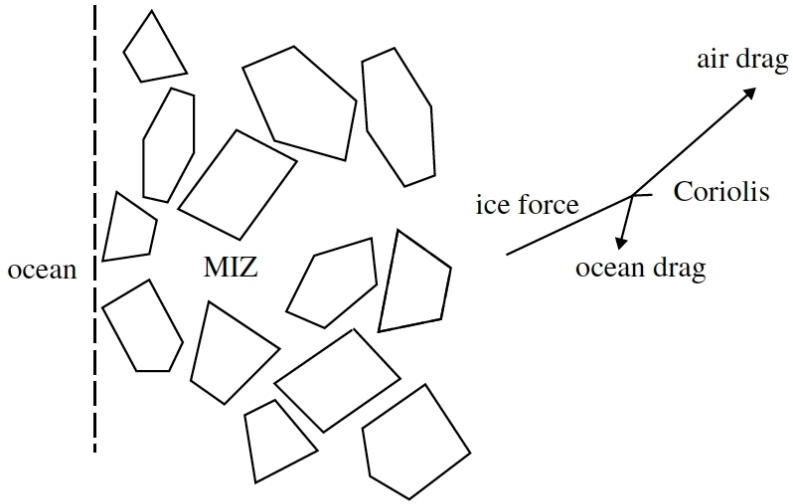


From: *Dumont et al (2011) J. Geophy. Res.*

Ocean/atmosphere coupling

Dynamics

- Smaller floes provide less resistance to winds and currents.
- Can be open water between the floes.
- Waves cause radiation stress.
- Random component of motion is likely to be important and cause collisions.

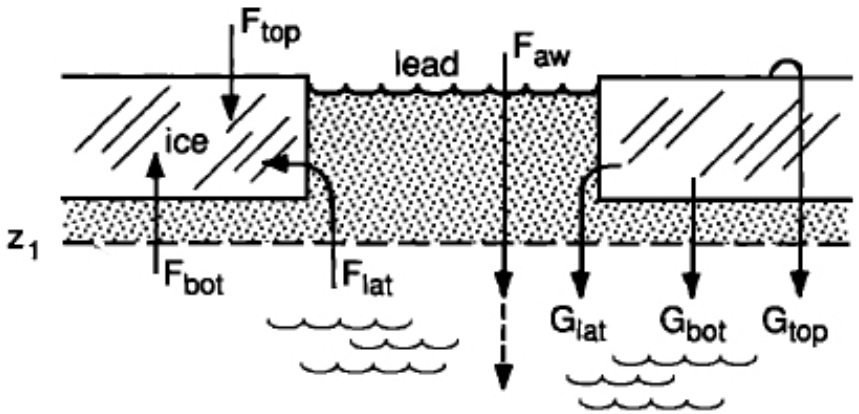


From: *Feltham (2005) Proc. Roy. Soc.*

Ocean/atmosphere coupling

Thermodynamics

- Smaller floes are more likely to melt (in summer).
- Open water between floes promotes freezing (in winter).



From: *Steele (1989) J. Geophys. Res.*

Ocean/atmosphere coupling

Possible other impacts

- FSD affect on atmosphere-ocean momentum flux, e.g. increase in roughness via floe edges (Uotila, 2001).
- Overwash of floes by waves increasing melting.
- Change to average albedo.
- ⋮
- Ideas welcome!!!!

CICE flux coupler

	Atmosphere		Ocean
	Provided by the flux coupler to the sea ice model		
z_o	Atmosphere level height	F_{frzmlt}	Freezing/melting potential
$\vec{U}_a$	Wind velocity	T_w	Sea surface temperature
Q_a	Specific humidity	S	Sea surface salinity
ρ_a	Air density	∇H_o	Sea surface slope
Θ_a	Air potential temperature	$\vec{U}_w$	Surface ocean currents
T_a	Air temperature		
$F_{sw\downarrow}$	Shortwave radiation (4 bands)		
$F_{L\downarrow}$	Incoming longwave radiation		
F_{rain}	Rainfall rate		
F_{snow}	Snowfall rate		
	Provided by the sea ice model to the flux coupler		
$\vec{\tau}_a$	Wind stress	$F_{sw\Downarrow}$	Penetrating shortwave
F_s	Sensible heat flux	F_{water}	Fresh water flux
F_l	Latent heat flux	F_{hocn}	Net heat flux to ocean
$F_{L\uparrow}$	Outgoing longwave	F_{salt}	Salt flux
F_{evap}	Evaporated water	$\vec{\tau}_w$	Ice-ocean stress
α	Surface albedo (4 bands)		
T_{sfc}	Surface temperature		
	a_i Ice fraction		
	T_a^{ref} 2 m reference temperature (diagnostic)		
	Q_a^{ref} 2 m reference humidity (diagnostic)		
	F_{swabs} Absorbed shortwave (diagnostic)		

Table 1: Data exchanged between the CCSM flux coupler and the sea ice model.

Experimental recordings of waves in ice

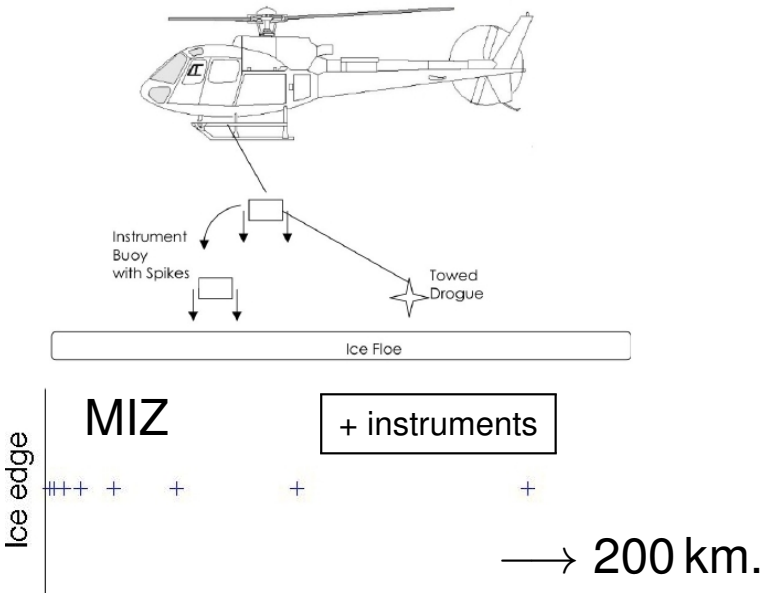
What's known

- Wave attenuation vs distance is a negative exponential.
- Attenuation increases for smaller wave periods, although there is evidence of rollover.
- Collimation and spreading of the wave field both reported.
- Waves induce floe breaking.

What's needed

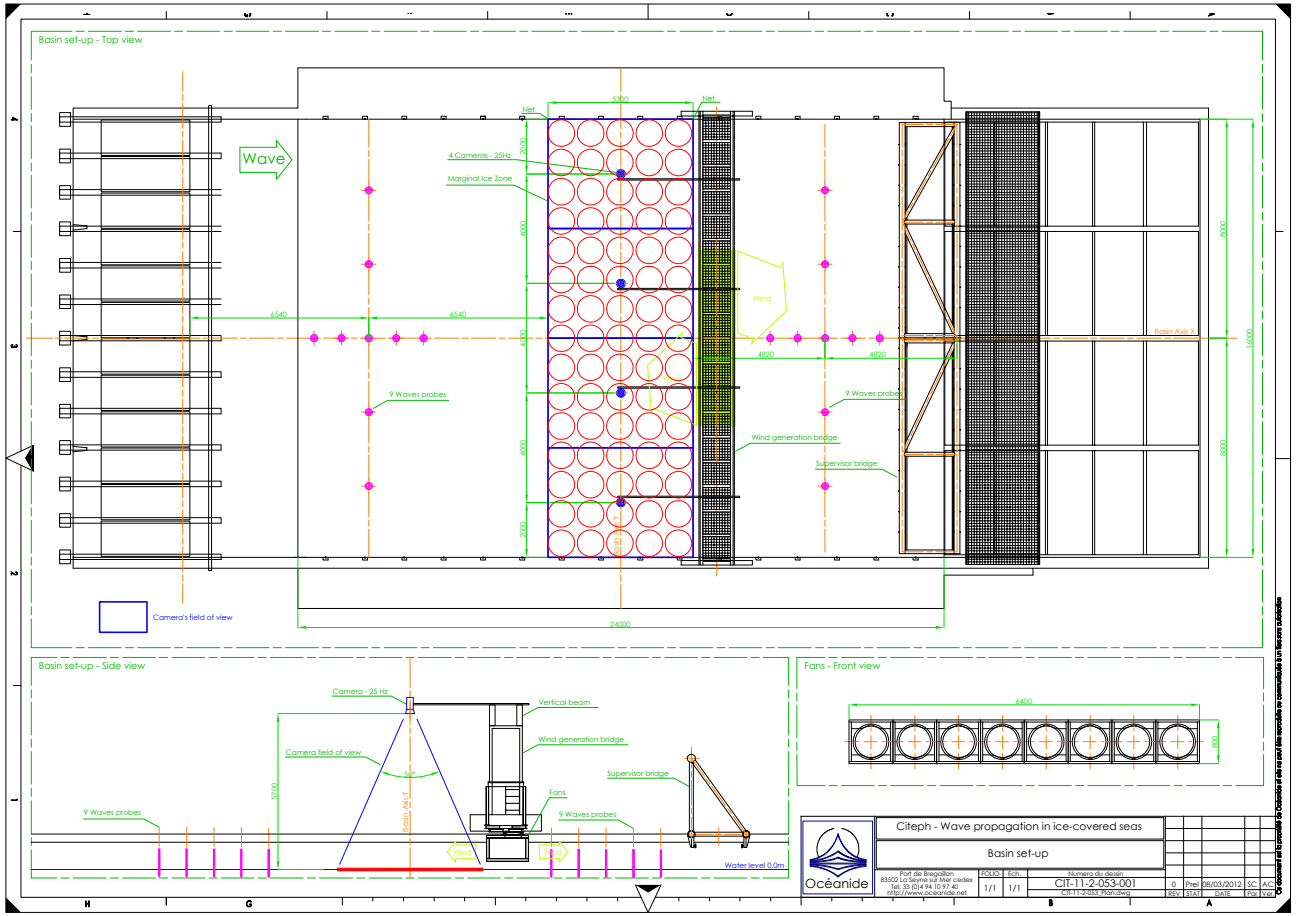
- Detailed descriptions of the evolution of waves in the MIZ along with information on the prevailing ice conditions and the incoming wave field.
- Measurements of floe breaking events, along with ice properties and local wave field.
- Recordings of the medium to large scale motion of the MIZ, along with ice properties and forcing fields.

Experimental recordings of waves in ice



- Alison Kohout (NIWA, NZ) will perform a wave attenuation experiment in East Antarctic during SIPEX II (Sept–Oct 2012).
- Wave activity in the MIZ will be recorded by an array of accelerometers mounted on floes.

Experimental recordings of waves in ice

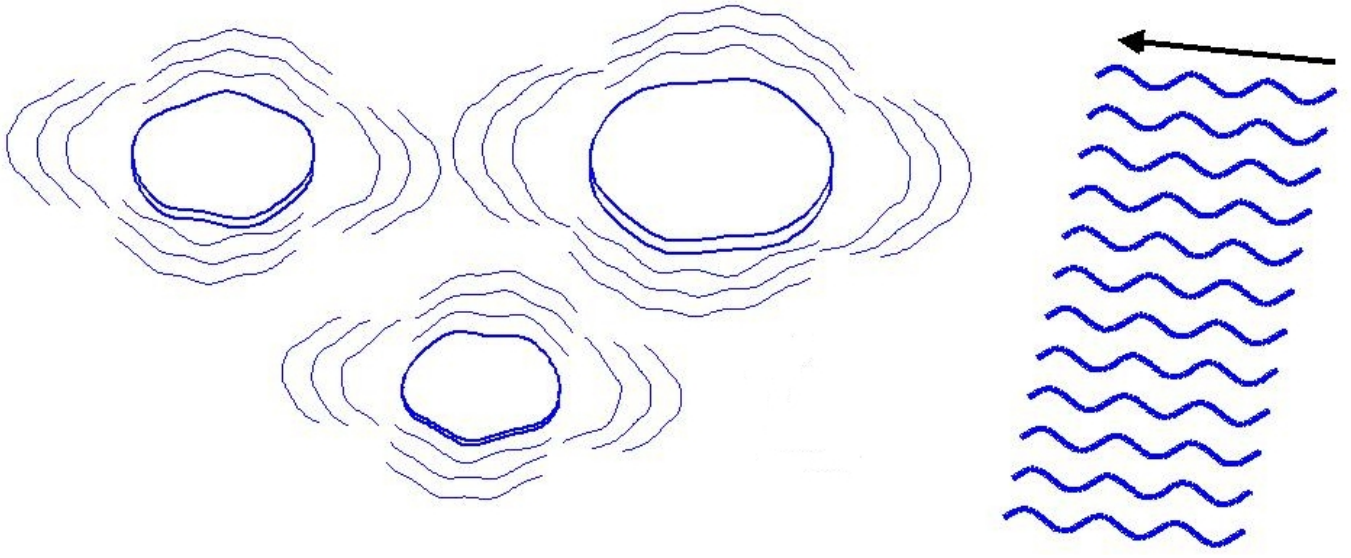


- Perform tests on a ‘mini MIZ’ $\sim$ 100 ‘floes’ in a wave tank in La Seyne, France (late 2012).
- Measure attenuation and rheology for a variety of wave, wind and current conditions.

Modelling wave propagation

Scattering models

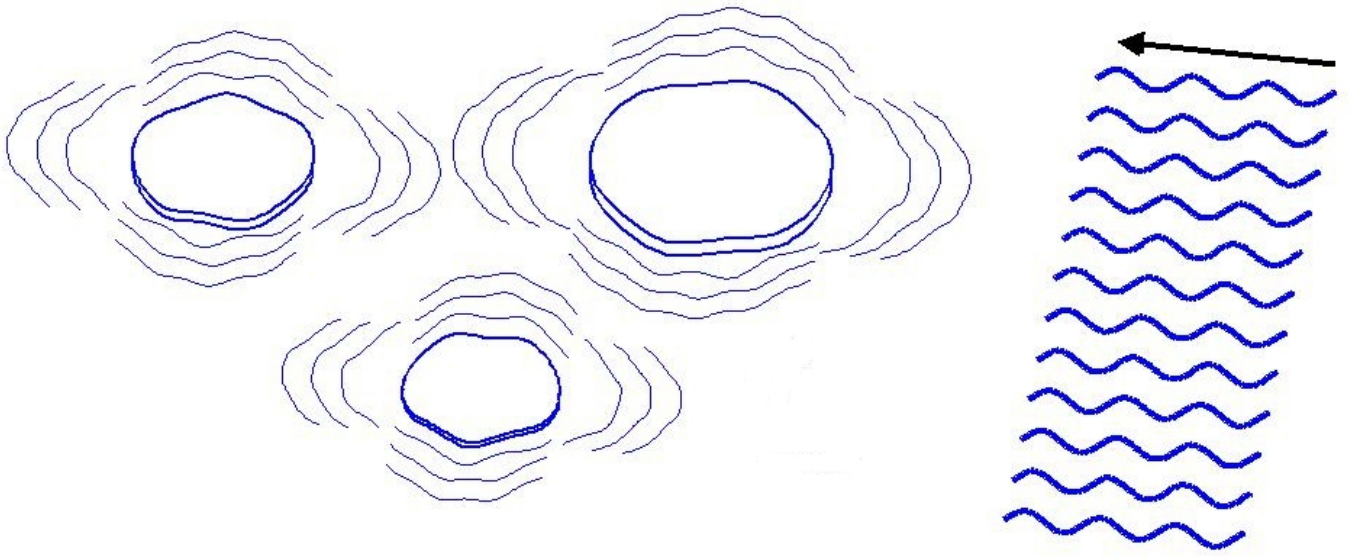
- Proposed in 1970s by Wadhams.
- Models based on linear theory/ice as a thin-elastic plate.
- Only recently have theory and computing power become adequate to model a full MIZ.
- Models reproduce exponential attenuation.
- Attenuation rate function of wave period and ice properties.
- Directional evolution of waves still not well understood.



Modelling wave propagation

Non-scattering attenuation.

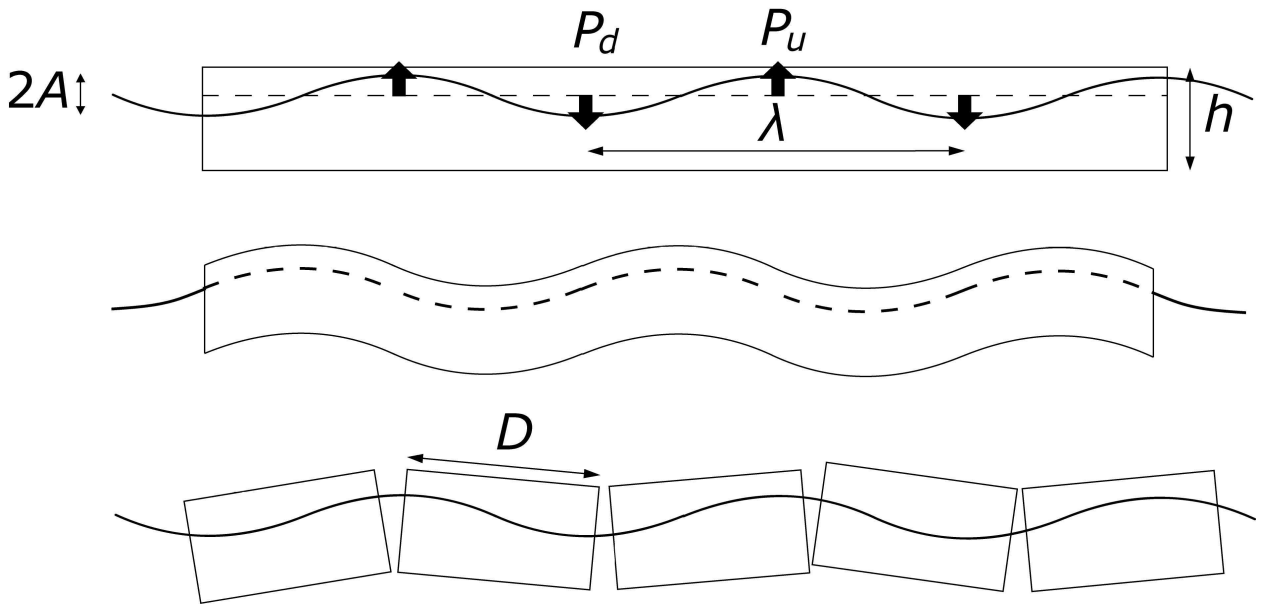
- Important, especially for large periods.
- However, poorly understood and modelled.
- Currently simulated through artificial ‘eddy’ viscosity.
- Some models of hysteresis (Wadhams, 1973; Shen & Squire, 1998).
- Idealised model of floe collisions by Rottier (1992), J. Geophy. Res.



Modelling floe breaking

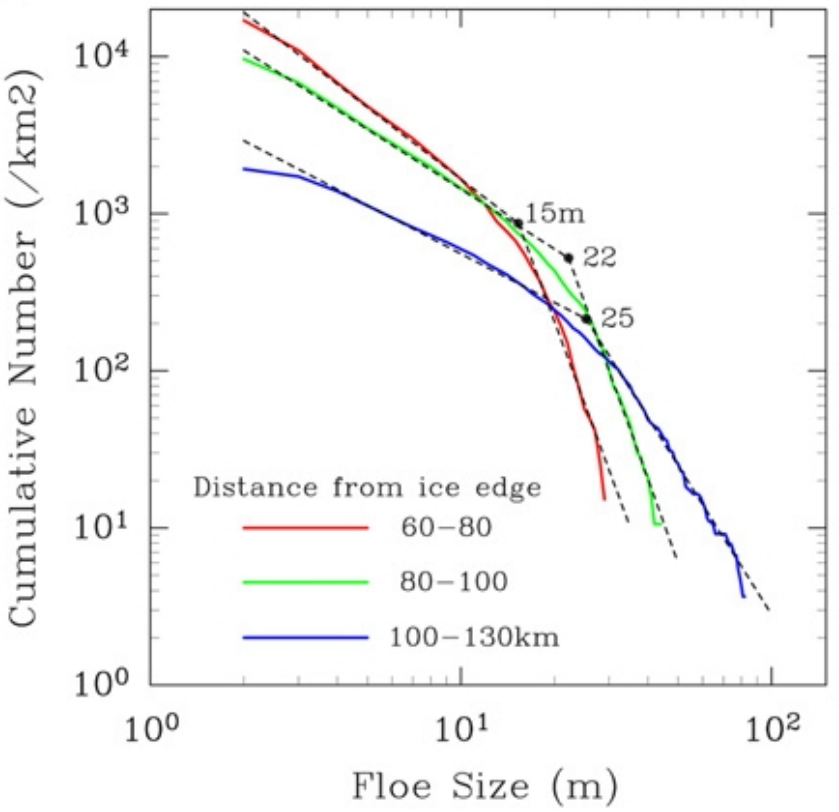
Wave-induced fracture

- Comparatively little modelling of floe breaking.
- More measurements of flexural strength than failure strain.
- Stresses/strains modelled using thin-plate theory.
- Lots of idealisations inherent in models.
- More information on constitutive relations needed near breaking limit.



Floe size distribution

- Bridge from small to large scales.
- FSDs found to obey a (pareto) power-law distribution, i.e. scale invariant.
- However, regime change between small/large floes noted by Toyota et al (2006, 2011).
- Small floes mainly influenced by waves, large floes by wind/current stresses.



From: *Toyota et al (2011) Deep Sea Res.*

MIZ rheology

Motivation

- The elastic viscous plastic rheology is appropriate for slow deformations, characteristic of the central pack ice.
- MIZ is a very active region.
- Responds very differently to oceanic/atmospheric forcing.

Collisional rheology of Shen et al (1987), J. Geophy. Res.

- Momentum transferred between floes through collisions.
- Assumes random component of floe motions is much larger than mean velocity.
- Intended as a component of a MIZ rheology.

Granular rheology of Feltham (2005), Proc. Roy. Soc.

- Combined plastic and collisional interactions in a composite rheology.

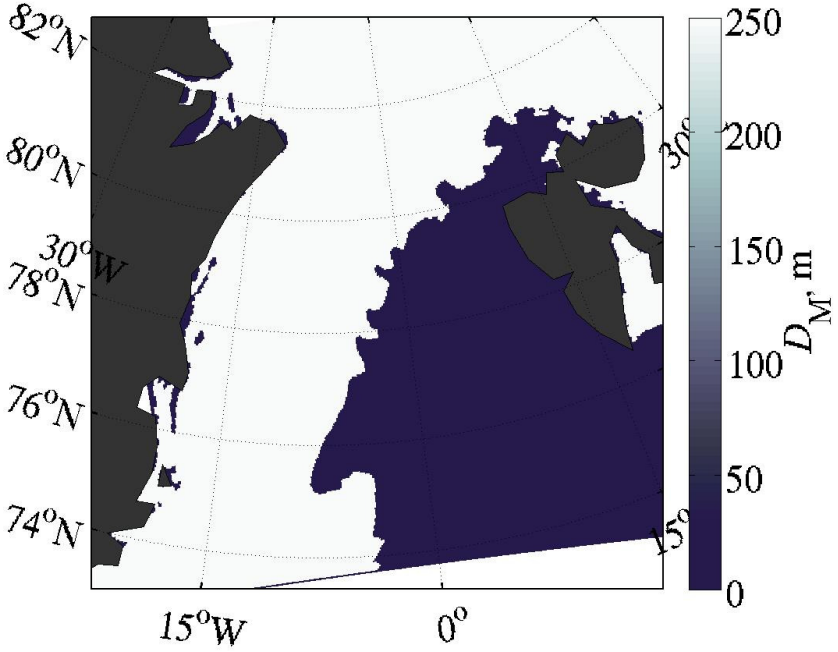
Project WIFAR

Project overview

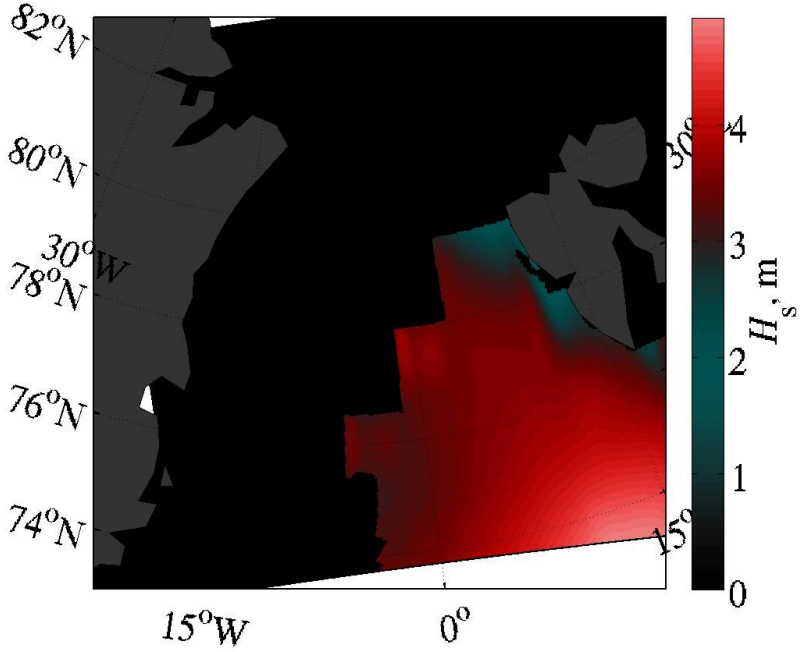
- Project goal is to incorporate wave-ice interactions into an operational forecasting model for the first time.
- High resolution models $\sim 3.5\,\text{km}$ of regions of operational interest are nested in a version of HYCOM.
- An incident wavefield (from WAM) is propagated numerically into the ice cover, and for each point in time/space the following algorithm is applied:
  1. Waves are attenuated according to local ice properties, using a pre-calculated 'look up table'.
  2. A strain floe breaking criterion is implemented. If breaking occurs the max floe size is set as $\frac{1}{2}$ dominant wavelength.
  3. This value is used in the model of Toyota (2011) to determine the local FSD.
  4. When the wave is fully attenuated the area of broken floes is defined as the MIZ and the collisional rheology of Shen et al (1987) is applied.

WIFAR preliminary results Fram Strait

Max Floe Diameter



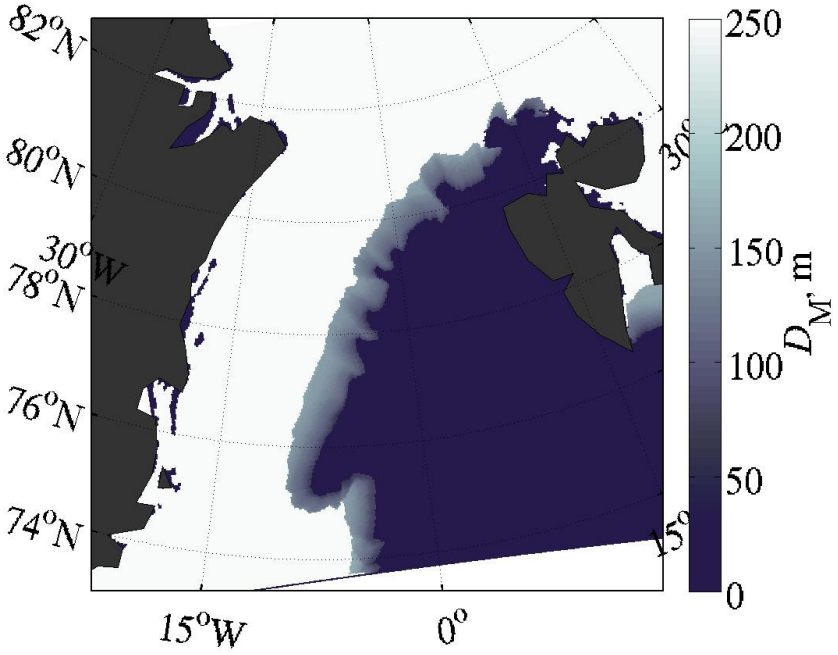
Significant wave height



- 10 wave directions and 22° resolution
- Max floe diameter is initially set to a large value (250 m) across ice-covered region

WIFAR preliminary results Fram Strait

Max Floe Diameter



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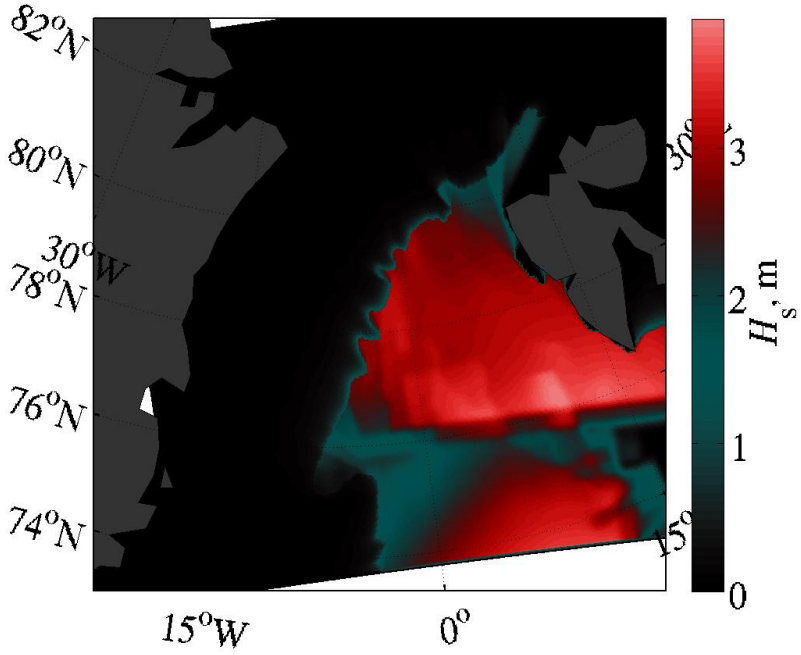
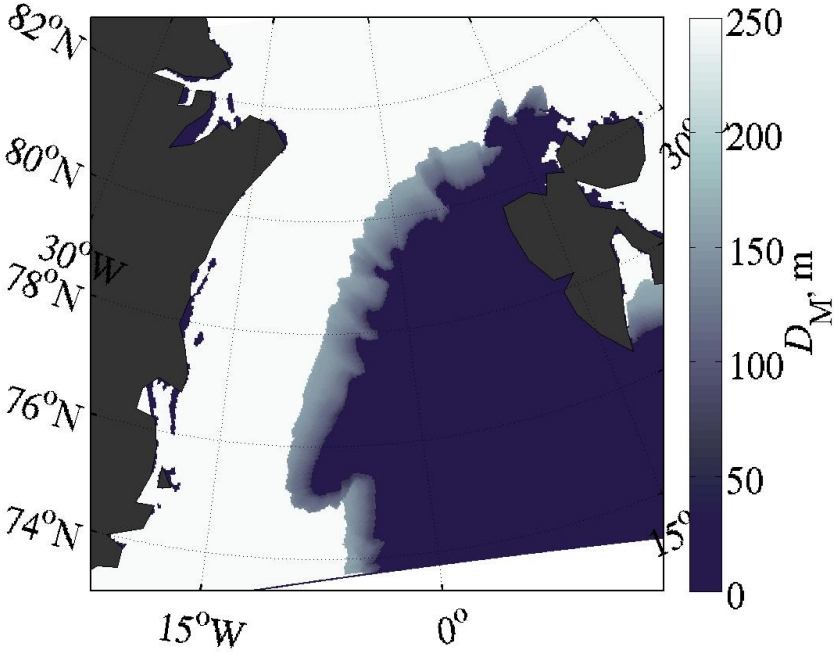


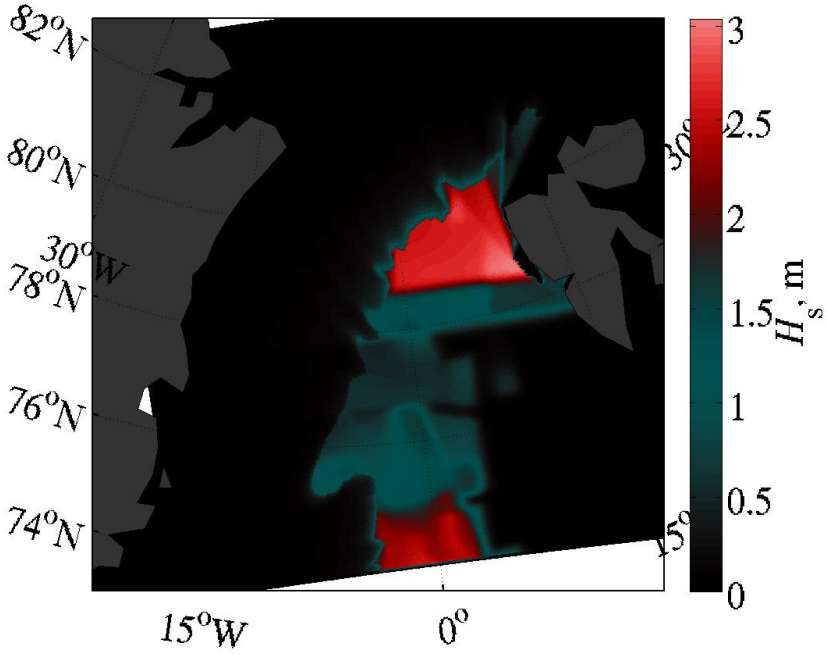
- Waves propagate into the ice-covered region and
  - Break the ice at the edge into smaller floes (left panel)
  - Are attenuated by the ice-cover (right panel)

WIFAR preliminary results Fram Strait

Max Floe Diameter



Significant wave height



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WIFAR preliminary results Fram Strait

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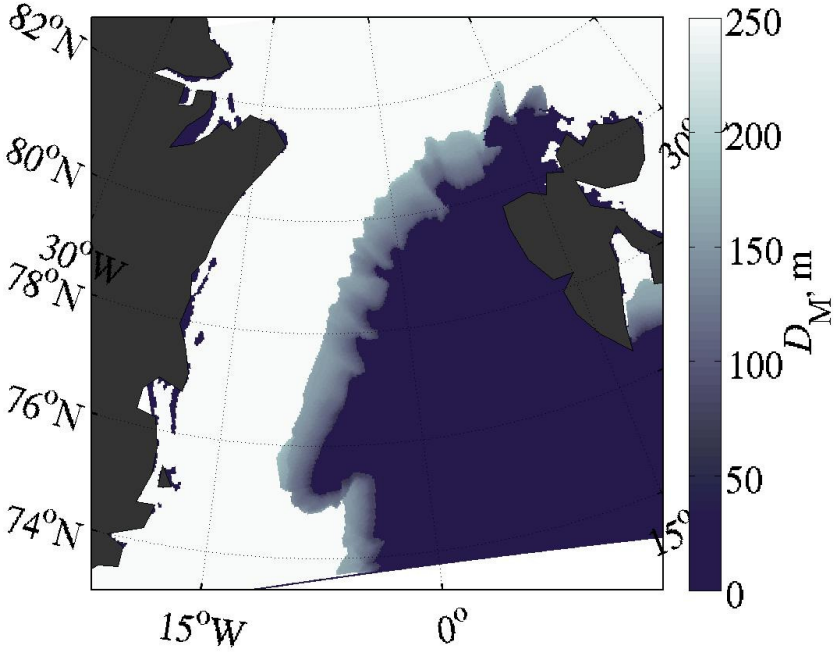
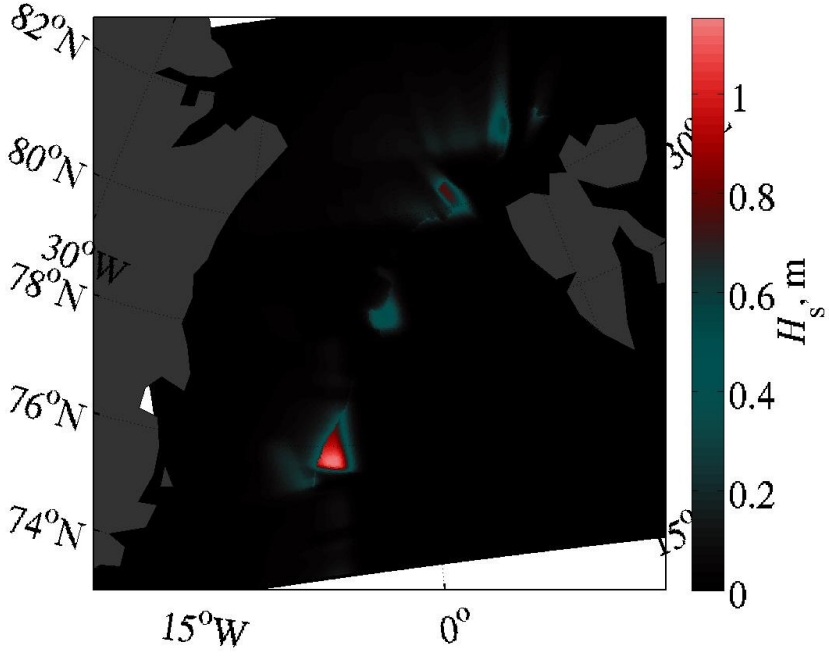
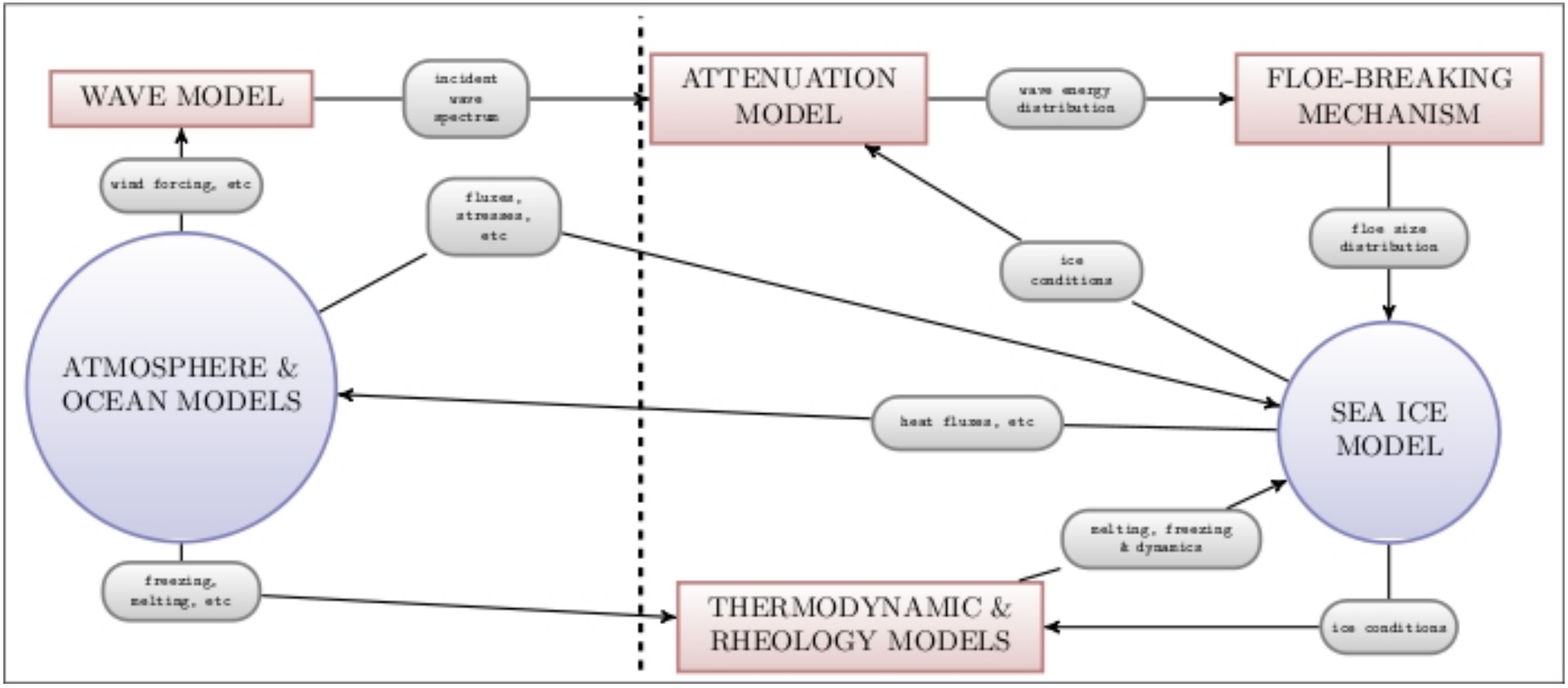


Significant wave height



- Until the waves are attenuated to a degree that they can no longer break the ice

Future: A FSD in CICE/ACCESS



- Primarily intended to enhance climate predictions.
- Basis of a project proposed by Siobhan O'F., Petteri U., Vernon S., myself and others.

Future: Remote sensing

FSD validation

- Need imagery able to resolve MIZ FSD.
- SAR doesn't appear to offer this?!?
- Landsat has been suggested.
- Aerial photo mosaics also used, but are limited in scale.